The final measurement of ϵ'/ϵ by NA48

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The direct CP violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$ has been measured from the decay rates of neutral kaons into two pions using the NA48 detector at the CERN SPS. The 2001 running period was devoted to collecting additional data under varied conditions compared to earlier years (1997-99). The 2001 data yield the result: $\mathrm{Re}(\epsilon/\epsilon') = (13.7 \pm 3.1) \times 10^{-4}$. Combining this result with that published from the 1997,98 and 99 data, an overall value of $\mathrm{Re}(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$ is obtained from the NA48 experiment.

1. INTRODUCTION

1.1. CP violation in the neutral kaon system

CP violation has been discovered in the neutral kaon system in 1964 [1]. The main component of the effect [2] occurs in the mixing between K_0 and $\overline{K_0}$. The physical states K_S and K_L deviate from pure CP = $\pm$ 1 eigenstates, with the mixing described by the parameter ϵ. Direct CP violation can occur in kaon decays to two pions through the interference of amplitudes with different isospins [3]. This is described by the parameter ϵ'. The quantity which can be measured experimentally is the double ratio R of the decay widths:

$$\begin{aligned} R &= \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \\ &\approx 1 - 6 \times Re(\epsilon'/\epsilon) \end{aligned}$$

In the Standard Model, CP violation arises from the irreducible complex phase in the CKM matrix [4]. Direct CP violation is predicted by the Standard Model, with typical computations for $\mathrm{Re}(\epsilon'/\epsilon)$ ranging from $\approx$ -10 to 30 $\times 10^{-4}$ [5].

From the data taken in 1997-98-99, NA48 published [6] a result $(15.3 \pm 2.6) \times 10^{-4}$. KTeV [7] published a result based on the data taken in 1996-1997 $(20.7 \pm 2.8) \times 10^{-4}$. These recent results showed the existence of direct CP violation in the neutral kaon system.

We report here on the measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ performed using the 2001 data sample, recorded in somewhat different experimental conditions by the NA48 experiment.

After the 1999 data-taking period, the drift chambers of the experiment were damaged by the implosion of the beam tube. The data taking in 2001 took place with rebuilt drift chambers. Thanks to the possibility of a better SPS duty cycle, the data could be taken at a 30% lower beam intensity, allowing the insensitivity of the result to intensity-related effects to be checked, and the statistics for the final ϵ'/ϵ measurement by NA48 to be completed. The statistics accumulated during the 2001 data-taking period is roughly half of the total statistics accumulated in the 1998 and 99 periods. The details of the analysis of this data set can be found in [8].

1.2. NA48 Method

The measurement of R proceeds by counting the number of events in each of the four decay modes. The experiment is designed to exploit cancellations of systematic effects contributing symmetrically to different components of the R. Data are collected simultaneously in the four decay modes, cancelling the absolute fluxes and

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minimising the sensitivity of the measurement to accidental activity and variations of the detection efficiency. The K_L and K_S decays are provided by two nearly collinear beams. To minimise the difference in acceptance due to the large difference in average decay lengths, only K_L decays occurring in the region also populated by K_S are used. The K_L events are furthermore weighted as a function of the proper lifetime in order to equalise the decay vertex distribution of K_L and K_S events. With this procedure, the acceptance correction cancels at first order in R, thus minimising the systematic uncertainty from Monte Carlo modelling of the experiment.

2. BEAMS AND DETECTOR

2.1. Beams

The neutral beams are derived from 400 GeV/c protons extracted from the CERN SPS. Because of the different mean decay lengths of K_L and K_S, two different production targets are used, located 126 m and 6 m upstream of the beginning of the decay region. For each SPS pulse (5.2 s every 16.8 s), $\approx 2.4\times10^{12}$ protons hit the K_L production target. Three stages of collimation are used to define the K_L beam, at a production angle of 2.4 mrad. Part of the non-interacting protons impinge on a bent silicon mono-crystal. A small fraction undergoes channelling and produces a proton beam of $\approx 5\times10^{7}$ protons per pulse transported to the K_S production target, where a second neutral beam is derived, at a production angle of 4.2 mrad. The K_S beam enters the fiducial decay region 6.8 cm above the K_L beam. The beams converge with an angle of 0.6 mrad and the axes of the two beams cross at the position of the electromagnetic calorimeter. To distinguish K_L and K_S decays, the protons directed to the K_S target are detected by an array of scintillation counters which comprise the tagging detector. The time of each proton is recorded and is compared with the time of the decay as measured in the main detector. The presence (absence) of a proton in coincidence with the event defines the event as K_S (K_L). The K_S beam traverses an anti-counter (AKS), formed by a set of scintillation counters following a 3 mm thick iridium crystal. This detector provides an accurate definition of the beginning of the decay region where it is located by vetoing K_S decays occurring upstream.

2.2. Main detector

Charged pion decays are measured by a magnetic spectrometer comprised of four drift chambers and a dipole magnet giving a momentum kick of 265 MeV/c. The momentum resolution is $\sigma_p/p = 0.48\% \oplus 0.009\% \times p$ (p in GeV/c). Two plastic scintillator hodoscope planes are located after the spectrometer. They are used to determine the event time of the charged events for the tagging procedure.

A quasi-homogeneous liquid krypton electromagnetic calorimeter with a projective tower readout is used to measure the photons from $\pi^0\pi^0$ events. The 13212 readout cells have each a cross-section of $\approx 2\times2$ cm^2. The energy resolution is $\sigma(E)/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$, where E is in GeV. The spatial resolution is better than 1 mm above 25 GeV. This detector is also used to measure the time of the photons for the tagging procedure.

Located after the electromagnetic calorimeter are a iron-scintillator hadron calorimeter, followed by a muon counter consisting of three planes of scintillators sandwiched between 80 cm thick iron walls.

2.3. Trigger

The electromagnetic calorimeter is used to trigger on $\pi^0\pi^0$ events. At the trigger level, the calorimeter data are reduced to x and y projections which are used to reconstruct the total energy as well as to estimate the decay position of the event. The efficiency of the $\pi^0\pi^0$ trigger is $(99.901 \pm 0.015)\%$ and is K_S-K_L symmetric. A two level trigger is used for $\pi^+\pi^-$ decays. At first level, the hodoscope is placed in coincidence with a total energy condition defined using both calorimeters. The second level trigger uses information from the drift chambers to perform a fast event reconstruction. The efficiency of the $\pi^+\pi^-$ trigger is $(98.697 \pm 0.017)\%$. This is higher by 0.9% than for the 1998-99 data thanks mostly to the lower beam intensity. The efficiency is mea-

sured separately for K_S and K_L and the double ratio is corrected for the small difference.

3. EVENT RECONSTRUCTION AND SELECTION

$K \to \pi^0\pi^0$ decays are selected using only data from the LKr calorimeter. The details of the reconstruction and of the cuts applied can be found in [8] and [6]. From the measured energies and impact point positions on the calorimeter of the four showers, the decay vertex position along the beam axis is computed assuming that their invariant mass is the kaon mass. The invariant mass of the two photons pairs are then computed (the resolution is better than 1 MeV/c^2) and compared to the nominal π^0 mass, constructing a χ^2 variable. To reject the residual background from $K_L \to 3\pi^0$ events, a cut on χ^2 is applied. This residual background fraction is $(5.6 \pm 2.0) \times 10^{-4}$ in the K_L sample, while the K_S sample is background free. The background from K_S decays produced by scattering of beam particles in the collimators in the K_L beam is $(8.8 \pm 2.0) \times 10^{-4}$.

$K \to \pi^+\pi^-$ decays are reconstructed from tracks in the spectrometer. In the $\pi^+\pi^-$ mode, both the longitudinal and the transverse decay vertex position can be reconstructed, allowing a clean identification of K_S and K_L decays. A cut is applied on the ratio of the two track momenta to remove asymmetric decays in which one of the tracks could be close to the beam tube where the Monte Carlo modelling is more critical. To reject background from semileptonic K_L decays, events with tracks consistent with being either an electron (from the E/p ratio of the energy deposited in the LKr calorimeter over the track momenta) or a muon (using hits in the muon counters) are rejected. Kinematical cuts are also applied on the $\pi^+\pi^-$ invariant mass (the resolution is typically 2.5 MeV/c^2) and on the reconstructed transverse momentum. The residual background in the K_L sample is $(14.2 \pm 3.0) \times 10^{-4}$, while it is negligible in the K_S sample.

The fiducial ranges in kaon energy E_K and in proper time τ used to count events are chosen to be $70 < E_K < 170$ GeV and $0 < \tau < 3.5\ \tau_S$, where $\tau = 0$ is defined at the position of the AKS counter and τ_S is the K_S mean lifetime. For K_L events, the decay time cut is applied on reconstructed τ, while for K_S events the cut at $\tau = 0$ is applied using the AKS to veto decays occurring upstream. The determinations of the kaon energy, the decay vertex and the proper time in the $\pi^0\pi^0$ mode rely on measurements of the photon energies and positions with the calorimeter. The uniformity of the calorimeter response is optimised using K_{e3} decays and checked using π^0 and η decays produced during special ("η") runs in which a π^- beam strikes two thin targets located near the beginning and the end of the fiducial decay region. The absolute energy scale is adjusted, with a 0.03% accuracy, using $K_S \to \pi^0\pi^0$ decays, such that the reconstructed AKS position matches the true value. It is also checked using data from the η runs (the η mass is taken from [9]). Taking all uncertainties into account (including non-linearities in the energy response), the total systematic uncertainty on R from the reconstruction of $\pi^0\pi^0$ events is found to be $\pm 5.3 \times 10^{-4}$ [8]. The uncertainty on R from the reconstruction of $\pi^+\pi^-$ events is $\pm 2.8 \times 10^{-4}$.

A decay is labelled K_S is a coincidence is found within a $\pm$ 2 ns interval between its event time and a proton time measured with the tagger. Figure 1 shows the time distribution for K_S and K_L decays to $\pi^+\pi^-$ which have been identified by their vertex positions. From this, the misidentification probabilities in the $\pi^+\pi^-$ mode can be deduced: $\alpha_{SL} = (1.12 \pm 0.03) \times 10^{-4}$ for the K_S tagging inefficiency and $\alpha_{LS} = (8.115 \pm 0.010)\%$ for the K_L mistagging as K_S due to an accidental coincidence between the event and a proton. As the same tagging procedure is used for $\pi^0\pi^0$ and $\pi^+\pi^-$ events, R is only sensitive to differences in misidentification probabilities between the $\pi^0\pi^0$ and $\pi^+\pi^-$ modes. Several methods have been developed to derive these differences directly from the data [8]. The results are $\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$ and $\Delta\alpha_{LS} = (3.4 \pm 1.4) \times 10^{-4}$ corresponding respectively to an uncertainty on R of $\pm 3.0 \times 10^{-4}$ and a correction of $(6.9 \pm 2.8) \times 10^{-4}$. The origin of $\Delta\alpha_{LS}$ is related to a higher loss of $\pi^+\pi^-$ events from accidental activity in the beam and can be predicted using a technique of overlaying "random" events (taken proportionally to the

beam intensity) with $\pi\pi$ decays to estimate these losses. The agreement between the observed and the predicted $\Delta\alpha_{LS}$ values is illustrated in Figure 2.

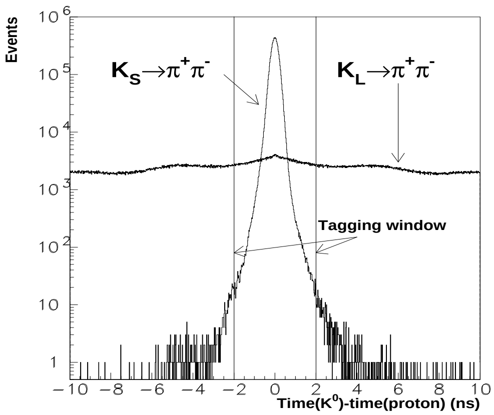

Figure 1. Time coincidence for K_S and K_L $\pi^+\pi^-$decays, identified by their reconstructed vertex position.

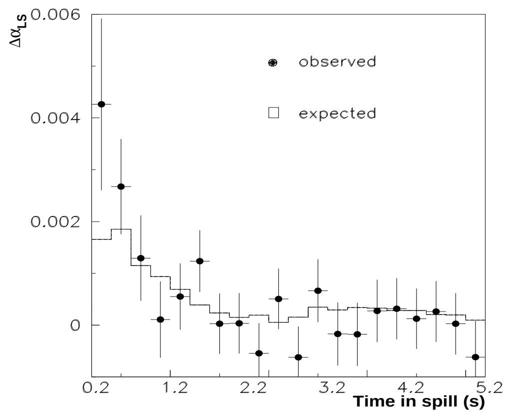

Figure 2. Measured compared to predicted values of $\Delta\alpha_{LS}$ as a function of the time during the spill.

4. ACCIDENTAL EFFECTS

The 2001 data were taken at lower beam intensity to reduce the uncertainties related to accidental effects. The overlap of extra particles related to kaon decays in the high intensity K_L beam with a good event may result in the loss of the event. The effect on R is minimised by the simultaneous data collection in the four channels. The possible residual effect on R can be separated into two components:

1) A difference between the beam intensities seen by K_S and K_L events: $\Delta R = \Delta\lambda \times \Delta I/I$, where $\Delta\lambda$ is the difference between the event losses in the $\pi^+\pi^-$ and $\pi^0\pi^0$ modes and $\Delta I/I$ the difference between the K_L beam intensity seen by K_L and K_S events. $\Delta\lambda$ is minimised by applying to all events the recorded dead time conditions. The largest one is an "overflow" condition in the drift chamber readout, which rejects 11% of the $\pi\pi$ events (this is significantly smaller than the 20% loss in the 1998-99 sample thanks to the lower beam instantaneous intensity and a lower noise in the drift chambers). $\Delta\lambda$ is estimated mainly from the overlay technique and is found to be (1.0±0.5)%. $\Delta I/I$ is measured from the rate of out-of-time LKr clusters and tracks in good K_S and K_L decays. This is illustrated in Figure 3. Beam monitors, which have been improved for the 2001 data-taking period, are also used as cross-check. The result is $\Delta I/I = (0{\pm}1)\%$. The uncertainty on R from this effect is thus $\pm 1.1 \times 10^{-4}$. This is significantly better than for the 1998-99 sample, thanks to the lower intensity and to better beam intensity monitors.

2) A difference in illumination between K_S and K_L decays coupled to a variation of the event loss with the impact points of the K^0 decay products. This effect is also computed from the overlay samples. No effect is found and the uncertainty on R is $\pm 3.0 \times 10^{-4}$, from the statistics of the overlay samples.

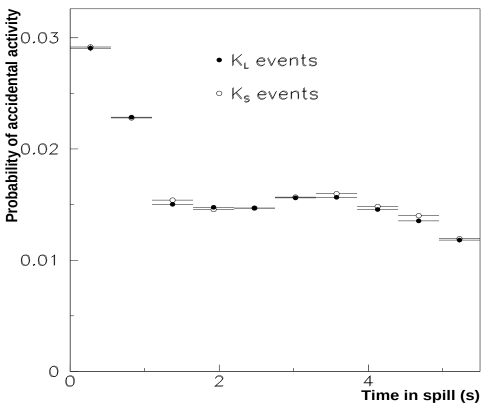

Figure 3. Probability of accidental activity in the LKr in the ≈ 150 ns readout window as a function of the time during the spill, for K_S and K_L decays to $\pi^+\pi^-$.

5. RESULT AND CONCLUSIONS

Table 1 shows the summary of the corrections and systematic uncertainties on R for 2001 data. The residual acceptance correction is related to the small angle between the K_L and K_S beams and is computed using a large statistics Monte Carlo sample. As it is mostly given by the beam geometry, it does not rely on a detailed simulation of the detector. As expected from the design of the experiment, all corrections are small. Some systematic uncertainties are directly given by the statistics of the control samples used to study them. From the 2001 sample (comprising 1.55×10^6 $K_L \to \pi^0\pi^0$ events, 2.16×10^6 $K_S \to \pi^0\pi^0$, 7.14×10^6 $K_L \to \pi^+\pi^-$ and 9.61×10^6 $K_S \to \pi^+\pi^-$), the result $\mathrm{R} = 0.99181 \pm 0.00147 \pm 0.00110$ is obtained (where the first error is statistical and the second systematic). The corresponding value of $\mathrm{Re}(\epsilon'/\epsilon)$ is $\mathrm{Re}(\epsilon'/\epsilon) = (13.7 \pm 2.5 \pm 1.8) \times 10^{-4}$. The agreement between this new and the earlier results is particularly significant since they were obtained from data taken at different average beam intensities. Taking into account the correlated systematic uncertainty of $\pm 1.4 \times 10^{-4}$, the final combined result from the NA48 experiment is $\mathrm{Re}(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$.

Table 1
Corrections and systematic uncertainties on R

		in 10^{-4}		
$\pi^+\pi^-$ trigger		+5.2	±3.6	(stat)
AKS inefficiency		+1.2	±0.3	
Reconstruction	of $\pi^0\pi^0$	—	± 5.3	
	of $\pi^+\pi^-$	—	± 2.8	
Background	to $\pi^0\pi^0$	−5.6	± 2.0	
	to $\pi^+\pi^-$	+14.2	± 3.0	
Beam scattering		−8.8	±2.0	
Accidental tagging		+6.9	±2.8	(stat)
Tagging inefficiency		—	±3.0	
Acceptance	statistical	+21.9	± 3.5	(stat)
	systematic		± 4.0	
Accidental effect	intensity	—	±1.1	
	illumination		±3.0	(stat)
K_S in time activity		—	±1.0	
Total		+35.0	±11.0	

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